



# **Technologies for Fire and Damage Control and Condition Based Maintenance**

## *Final Report*

*John A. Hiltz*

**Defence R&D Canada – Atlantic**

Technical Memorandum  
DRDC Atlantic TM 2011-196  
December 2011

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This is the final report for Applied Research Project 11gy

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## Abstract

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This is the final report of Applied Research Program (ARP) project 11gy “Technologies for Fire and Damage Control and Condition Based Maintenance”. The project objective was to develop an improved understanding of how materials, sensors and sensor systems choices impact the sustainability and supportability of new build ships from both the damage control and condition based maintenance perspectives.

Specifications, standards and methods for the evaluation of the fire performance of non-metallic materials are reviewed. Although no one method can be used to rank materials, cone calorimetry is the test method that provides the most useful information on how materials might perform in a fire. A volume sensor system (VSS), named the Canadian Demonstrator Prototype (CDP), was purchased and evaluated on the United States Naval Research Laboratory fire research ship the ex-USS Shadwell. A volume sensor system monitors a space for fire and damage events using video and infrared cameras, infrared and ultraviolet spectral sensors and an acoustic sensor. The system also has data fusion software that analyses the sensor input and determines if the input is consistent with a fire or damage event or is the result of shipboard activities that are not related to fire and damage events. The results of the testing indicated that the system could differentiate between real fire and damage scenarios and shipboard activities and events that are not related to fire and damage events and could therefore reduce false alarms. A condition based monitoring (CBM) diesel engine lubricating oil sensor suite and system was developed and trialled on an operational Canadian Patrol Frigate. The goal of this program is to base maintenance on the condition of the engine and its oil as opposed to performing time based maintenance. This will enable ship’s crews to focus maintenance efforts on engines where it is required and eliminate maintenance when it is not required. The effectiveness of water mist fire suppression systems was modeled using one and two zone models and a computational fluid dynamics (CFD) model. The results of the modeling studies were compared to those from large scale fire tests to validate their accuracy. Improvements in the fire and flammability performance of polymeric materials using nano additives and other strategies were also investigated. It was found that some of the additives improved the fire and flammability performance of the polymeric materials substantially.

## Résumé

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Le présent document est le rapport final du projet 11gy intitulé « Technologies de lutte contre les incendies et les avaries et de maintenance selon l’état » dans le cadre du Programme de recherches appliquées (PRA). L’objectif de ce projet était de mieux comprendre la façon dont les matériaux, les capteurs et les systèmes de capteurs influent sur la durabilité et la soutenabilité des nouveaux navires en termes de lutte contre les avaries et de maintenance selon l’état (CBM).

Les spécifications, normes et méthodes pour l’évaluation de la tenue au feu des matériaux non métalliques sont examinées. Bien qu’aucune méthode ne permette à elle seule de classer les matériaux, la calorimétrie à cône est la méthode d’essai qui fournit les informations les plus utiles sur le comportement des matériaux dans un incendie. Un système de capteur de volume (VSS),

appelé « Canadian Demonstrator Prototype » (CDP), a été acheté et ses capacités ont été évaluées au cours d'essais sur l'ancien USS Shadwell, le navire de recherche sur les incendies du Naval Research Laboratory. Un système de capteur de volume surveille un espace ou une pièce afin de détecter les incendies et les avaries à l'aide de caméras vidéo et infrarouge, de capteurs dans l'infrarouge et l'ultraviolet et d'un capteur acoustique. Le système comporte également un logiciel de fusion des données qui analyse les données fournies par les capteurs et détermine si elles correspondent à un incendie ou des avaries, ou à d'autres événements. Les résultats des essais ont indiqué que le système pourrait différencier entre des conditions réelles d'incendie et d'avaries et les autres événements à bord qui ne sont pas liés à un incendie ou une avarie, ce qui pourrait donc réduire les fausses alarmes. Un système et un ensemble de capteurs pour la maintenance selon l'état (CBM) du circuit de graissage des moteurs diesel ont été développés et mis à l'essai sur une frégate canadienne de patrouille opérationnelle. L'objectif de ce programme est d'assurer la maintenance de base selon l'état du moteur et de son circuit de graissage, au lieu de procéder à la maintenance selon un calendrier fixe. Les équipages du navire pourront ainsi concentrer leurs efforts de maintenance mécanique là où c'est requis, ce qui réduira la maintenance inutile. L'efficacité des systèmes d'extinction d'incendie par brouillard d'eau a été modélisée par des modèles à une et deux zones, basés sur la dynamique numérique des fluides. Les résultats des études de modélisation ont été comparés à ceux des essais à pleine échelle pour valider leur exactitude. Nous avons également étudié l'amélioration des propriétés de tenue au feu et d'inflammabilité des matériaux polymères en utilisant des nanoadditifs, ainsi que d'autres stratégies. Nous avons constaté que certains additifs améliorent ces propriétés de manière notable.

## Executive summary

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### Technologies for Fire and Damage Control and Condition Based Maintenance: Final Report

**John A. Hiltz; DRDC Atlantic TM 2011-196; Defence R&D Canada – Atlantic; December 2011.**

**Background:** This is the final report of Applied Research Program (ARP) project 11gy “Technologies for Fire and Damage Control and Condition Based Maintenance”. The project objective was to develop an improved understanding of how materials, sensors and sensor systems choices impact the sustainability and supportability of new build ships from both the damage control and condition based maintenance perspectives. It was comprised of the five work breakdown elements (WBEs).

A number of polymeric materials are used on ships because of their properties. However, polymeric materials will burn and pose a hazard in a fire situation. In this memorandum, the assessment of the fire and flammability properties of polymeric materials is reviewed and approaches to improving these properties discussed. The use of nano additives to improve the fire and flammability properties of polymeric materials was also investigated. Enhanced fire and damage detection on board ships will result in earlier detection of fire and damage events and decrease the risk associated with the spread of the fire or damage. Volume sensing and associated data fusion software provides a means of rapid and accurate detection of these events. A volume sensing system, named the Canadian Demonstrator Prototype, is described and the results of a shipboard evaluation on the Naval Research Laboratory fire test ship, the ex-USS Shadwell, are reported. One potential replacement for total flooding Halon fire extinguishment systems on board ships is a water mist extinguishment system. Full scale testing of a water mist system for a large ship board space, such as machinery space, is expensive. Models, including a computational fluid dynamics model that can simulate the extinguishment of a fire using water mist are evaluated. The results are compared to the results from full scale tests in an attempt to validate the models. The strengths and weaknesses of the models are discussed. Condition based maintenance is being introduced to reduce the time and cost associated with time based maintenance of shipboard systems such as auxiliary and propulsion diesel engines. Early detection of equipment problems using this technique should also reduce the number of catastrophic failure and increase the availability of the system and the operational readiness of the ship. A condition based monitoring system for diesel engine lubricating oil, developed at DRDC Atlantic, is described. The system is presently being trialled on an operational Canadian Patrol Frigate.

**Results:** In the first WBE, “Evaluation of Commercial off the Shelf Fire and Damage Tolerant Non-metallic Materials”, the pertinent standards, specifications, and tests for the evaluation of the fire and flammability properties of non-metallic materials were reviewed. Although no test or suite of tests can predict the performance of materials in a fire, testing can be used to compare properties of a series of materials and select those that pose the minimum threat in a fire situation.

The second WBE, Fire/Damage Sensors and Systems, a prototype volume sensor system was purchased and its performance evaluated in testing on the United States Naval Research

Laboratory fire research ship, the ex-USS SHADWELL. The Canadian Demonstrator Prototype volume sensor system (CDP-VSS) combines multiple sensors with local pre-processing and off-device data fusion to synthesize the discrete inputs and generate casualty alarm signals.

In the third WBE, Condition Based Monitoring (CBM) Sensors and Systems, a CBM system with the capability to provide a real-time assessment of a ship's entire charge of oil to shipboard personnel or the life cycle equipment manager was developed and tested on an operational Canadian Patrol Frigate. Real-time assessment of critical lubricant properties will allow operators to replace the lubricant based as required, as opposed to on a timed basis.

In the fourth WBE, Fire Suppression Systems for Halon Replacement, the applicability of modeling to the prediction of the effectiveness of water mist fire suppression was investigated. The ability of the Fire Dynamics Simulator (FDS) computational fluid dynamics (CFD) model to predict fire suppression results for large fires was evaluated.

In the fifth WBE, Novel Fire and Damage Tolerant Materials, approaches to improving the flammability properties of polyureas were investigated. Polyureas are candidate materials for use as explosion resistant coatings. Their flammability properties will have to be improved if they are to be used on navy vessels.

**Significance:** The knowledge of standards, specifications, and test protocols for the evaluation of the fire and flammability properties of non-metallic materials for shipboard will reduce the risk associated with non-metallic materials in a fire situation. These can be used to ensure that the materials selected for new ships present a minimal risk in a fire situation. Enhancing the fire and flammability resistance of non-metallic materials required on ships will also reduce risks involved with these materials in a fire situation. The enhanced fire and damage sensing capabilities provided by enhanced fire and damage sensors, such as the volume sensor system, will allow rapid detection and mitigation of fire and damage events. In addition, they will provide continuous monitoring of unmanned spaces for fire and damage events. Developments in CBM for lubricating oil systems have the potential to reduce costs and improve operational readiness of ship systems. CBM should reduce costs arising from the change out of oil based on time in service and give operators advanced notice of impending failures. Maintenance can then be focussed on systems that require it. The use of modeling to evaluate the effectiveness of a water mist system and its set-up can reduce costs associated with full scale fire testing of the system. It can also be used to evaluate the effectiveness of different systems prior to the selection of a one of them for full scale testing.

**Future plans:** The CBM system is presently being trialed on HMCS ST. JOHNS. Further testing and evaluation of the CDP-VSS system will be pursued.



## Sommaire

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### Technologies for Fire and Damage Control and Condition Based Maintenance: Final Report

**John A. Hiltz ; DRDC Atlantic TM 2011-196 ; R & D pour la défense Canada – Atlantique; décembre 2011.**

**Contexte :** Le présent document est le rapport final du projet 11gy intitulé « Technologies de lutte contre les incendies et les avaries et de maintenance selon l'état » dans le cadre du Programme de recherches appliquées (PRA). L'objectif de ce projet était de mieux comprendre la façon dont les matériaux, les capteurs et les systèmes de capteurs influent sur la durabilité et la soutenabilité des nouveaux navires en termes de lutte contre les avaries et de maintenance selon l'état (CBM). Le projet comportait cinq éléments de répartition du travail (ERT).

Plusieurs matériaux polymères sont utilisés sur les navires en raison de leurs propriétés. Toutefois, ces matériaux brûleront et poseront un risque en cas d'incendie. Dans cet exposé, nous examinons l'évaluation des propriétés de tenue au feu et d'inflammabilité des matériaux polymères et nous présentons les approches visant à améliorer ces propriétés. L'utilisation de nanoadditifs pour améliorer les propriétés de tenue au feu et d'inflammabilité des matériaux polymères a également été étudiée. Une meilleure détection des incendies et des avaries à bord des navires permettra leur détection plus rapide et diminuera les risques associés à la propagation des incendies ou des avaries. La détection des volumes et les logiciels connexes de fusion de données offrent un moyen de détection rapide et précise de ces événements. Nous décrivons un système de détection du volume, appelé « Canadian Demonstrator Prototype » (CDP), ainsi que les résultats d'une évaluation réalisée à bord de l'ancien USS Shadwell, le navire de recherche sur les incendies du Naval Research Laboratory. Un système d'extinction par brouillard d'eau pourrait remplacer les systèmes d'extinction par noyage total aux halons à bord des navires. Les essais à pleine échelle d'un système de brouillard d'eau dans un grand espace à bord des navires, comme les salles des machines, sont coûteux. Nous avons évalué des modèles, notamment un modèle s'appuyant sur la dynamique numérique des fluides, qui peuvent simuler l'extinction d'un incendie par brouillard d'eau. Les résultats sont comparés à ceux des essais à pleine échelle afin de valider les modèles. Nous décrivons les forces et les lacunes des modèles. La maintenance selon l'état est également introduite pour réduire le temps et les coûts de maintenance des systèmes embarqués, comme les moteurs diesel auxiliaires et de propulsion. La détection précoce des problèmes d'équipement à l'aide de cette technique devrait aussi réduire le nombre d'avaries catastrophique et accroître la disponibilité du système et l'état de préparation opérationnelle du navire. Nous décrivons un système de surveillance de l'état du circuit de graissage des moteurs diesel, mis au point à RDDC Atlantique. Le système est actuellement à l'essai sur une frégate canadienne de patrouille opérationnelle.

**Résultats :** Le premier ERT, « Évaluation de matériaux commerciaux tolérants aux incendies et aux avaries », portait sur les normes, spécifications et essais pertinents pour évaluer la tenue au feu et l'inflammabilité des matériaux non métalliques. Bien qu'aucun essai ou série d'essais ne puisse prévoir le comportement des matériaux dans un incendie, ces essais permettent néanmoins de comparer les propriétés d'une série de matériaux et de choisir ceux qui présentent le moins de risque dans une situation d'incendie.

Le deuxième ERT, « Capteurs et systèmes de détection d'incendies et d'avaries », consistait à acheter un système prototype de capteur de volume et à évaluer son rendement par des essais sur l'ancien USS Shadwell, le navire de recherche sur les incendies du Naval Research Laboratory. Le système prototype de capteur de volume appelé « Canadian Demonstrator Prototype » (CDP-VSS) combine plusieurs capteurs multiples avec des fonctions embarquées de prétraitement et hors dispositif de fusion de données pour synthétiser les entrées discrètes et générer des signaux d'alarme en cas d'avaries.

Dans le troisième ERT, « Capteurs et systèmes de maintenance selon l'état », un système CBM pouvant évaluer en temps réel la charge entière en huiles du navire pour le personnel de bord ou le gestionnaire du cycle de vie de l'équipement a été mis au point et testé sur une frégate canadienne de patrouille. L'évaluation en temps réel des propriétés lubrifiantes essentielles permettra aux mécaniciens de remplacer les lubrifiants au besoin, au lieu de le faire selon un calendrier fixe.

Dans le quatrième ERT, « Systèmes d'extinction d'incendie pour le remplacement des halons », nous avons étudié l'applicabilité de la modélisation pour établir l'efficacité des systèmes d'extinction d'incendie par brouillard d'eau. Nous avons aussi évalué la capacité du simulateur dynamique d'incendie, s'appuyant sur la dynamique numérique des fluides, afin de prévoir les résultats de la suppression des gros incendies.

Dans le cinquième ERT, « Matériaux nouveaux tolérants aux incendies et aux avaries », nous avons étudié des approches pour améliorer les propriétés d'inflammabilité des polyuréthes. Les polyuréthes pourraient être utilisées comme revêtements résistants aux explosions. Leurs propriétés d'inflammabilité devront être améliorées si on veut les employer sur les bâtiments de la marine.

**Importance :** La connaissance des normes, des spécifications et des protocoles d'essai pour l'évaluation des propriétés de tenue au feu et d'inflammabilité des matériaux non métalliques à bord des navires réduira les risques associés à ces matériaux en cas d'incendie. On peut les utiliser pour s'assurer que les matériaux choisis pour les nouveaux navires présentent un risque minimal dans de telles situations. L'amélioration des propriétés de tenue au feu et d'inflammabilité des matériaux non métalliques nécessaires sur les navires permettra aussi de réduire les risques associés à ces matériaux en cas d'incendie. Les capacités accrues de détection des incendies et des avaries, grâce à des capteurs améliorés comme les capteurs de volume, permettront la détection et l'atténuation rapides des incendies et des avaries. De plus, cela permettra une surveillance continue des espaces non habités pour la détection des incendies et des avaries. La mise au point d'un système CBM pour les circuits de graissage permettra de réduire les coûts et d'améliorer la disponibilité opérationnelle des systèmes du navire. Le système CBM devrait réduire les coûts du remplacement des lubrifiants d'après leur temps de service et aviser les mécaniciens en cas de défaillances imminentes. Les travaux de maintenance pourront alors porter sur les systèmes qui en ont besoin. Le recours à la modélisation pour évaluer l'efficacité d'un système de brouillard d'eau et sa mise en place peut réduire les coûts associés aux essais des systèmes à pleine échelle. La modélisation permet également d'évaluer l'efficacité des différents systèmes avant d'en choisir un pour les essais à pleine échelle.

**Plans futurs :** Le système CBM est actuellement à l'essai sur le NCSM St. John's. En outre, les essais et l'évaluation du système CDP-VSS se poursuivront.

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# 1 Introduction

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This is the final report of Applied Research Program (ARP) project 11gy “Technologies for Fire and Damage Control and Condition Based Maintenance”. The project objective was to develop an improved understanding of how materials, sensors and sensor systems choices impact the sustainability and supportability of new build ships from both the damage control and condition based maintenance perspectives. It was comprised of the five work breakdown element (WBEs) listed below.

## 1. Evaluation of Commercial off the Shelf Fire and Damage Tolerant Non-metallic Materials

A number of polymeric materials are used on ships because they have properties that are not available in other materials. However, polymeric materials will burn and pose a hazard in a fire situation. The standards, specification and tests used to assess the fire and flammability properties of polymeric materials are reviewed and approaches to improving these properties discussed.

## 2. Fire/Damage Sensors and Systems.

Enhanced fire and damage detection on board ships will result in earlier detection of fire and damage events and decrease the risk associated with the spread of the fire or damage. Volume sensing and associated data fusion software provides a means of rapid and accurate detection of these events. A volume sensing system, named the Canadian Demonstrator Prototype, is described and the results of a shipboard evaluation on the Naval Research Laboratory fire test ship, the ex-USS Shadwell, are reported.

## 3. Condition Based Monitoring (CBM) Sensors and Systems

Condition based maintenance is being introduced to reduce the time and cost associated with time based maintenance of shipboard systems such as auxiliary and propulsion diesel engines. Early detection of equipment problems using this technique should also reduce the number of catastrophic failures and increase the availability of the system and the operational readiness of the ship. A condition based monitoring system for diesel engine lubricating oil, developed at DRDC Atlantic, is described. The system is presently being trialled on an operational Canadian Patrol Frigate.

## 4. Fire Suppression Systems for Halon Replacement

One potential replacement for total flooding Halon fire extinguishment systems on board ships is a water mist extinguishment system. Full scale testing of a water mist system for a large ship board space, such as machinery space, is expensive. Models, including a computational fluid dynamics model that can simulate the extinguishment of a fire using water mist are evaluated. The results are compared to the results from full scale tests in an attempt to validate the models. The strengths and weaknesses of the models are discussed.

## 5. Novel Fire and Damage Tolerant Materials.

The use of nano additives to improve the fire and flammability properties of polymeric materials was investigated.

The results of the work breakdown elements are discussed in the following sections and are a summary of those from the reports generated in this Applied Research Program project.

## 2 Results

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### 2.1 Evaluation of Commercial Off-the-Shelf Fire and Damage Tolerant Non-Metallic Materials

Although the rapid detection and extinguishment of fires is a critical component of damage control, the risk and severity of shipboard fires can also be reduced through the selection of non-metallic materials that are less susceptible to ignition, have low rates of flame spread, generate less smoke, and release less heat and toxic gases than competing products. CRW Regulatory Services Inc. reviewed [1] standards for the fire performance of non-metallic materials, methods and apparatus used to evaluate the fire performance properties required by the standards, and models related to fire and discusses these with respect to their applicability to materials for Navy ships.

The review indicated that there are a large number of standards for the fire performance of non-metallic materials including those of the International Maritime Organization (IMO) and the International Standards Organization (ISO), US military specifications (Mil Spec) and Royal Navy Defence Standards (Def Stan) and associated Naval Engineering Standards (NES). The various standards, in turn, reference a large number of methods and apparatus for the evaluation of fire and flammability properties of non-metallic materials. The methods include ASTM (American Society for Testing and Materials), Underwriter's Laboratories (UL), ISO, and NES fire performance standards. The testing apparatus required for the material evaluation are referenced in the standards. These standards, methods and apparatuses are listed and discussed in the report. The US Military Standard (MIL-STD-1623E) specifications for fire tests are listed in Table 1.

The applicability of small scale/laboratory fire testing to the evaluation of non-metallic material performance in larger scale fire tests is also discussed in Reference 1. The acceptance criteria for a number of fire test methods are listed in Annex A and a summary of test methods from the UK Def Standard 07-247 Part 1 are listed in Annex B. Although there are many small scale/laboratory tests used to access the fire properties of non-metallic materials, no one test or suite of tests was found whose data correlated well with large scale test results for all materials and fire scenarios. However the cone calorimeter was determined to be the most applicable due to the amount of data generated with this test. This test is referenced in both the acceptance criteria shown in Annex A and the summary of test methods in Annex B.



Models developed to predict a range of fire related phenomena were also reviewed. These included one zone, two zone and computational fluid dynamic fire models and detector response, egress, and fire endurance models. As computing power increases and understanding of the fire process improves, these models will help designers and architects understand the risks associated with the use of materials and system designs and how these risks might be mitigated. The applicability of one zone, two zone and computational fluid dynamics models for the prediction of the fire suppression capabilities of water mist fire suppression systems are dealt with in greater detail in Section 2.4.

*Table 1- MIL-STD-1623E specifications for fire tests.*

<b>Specification</b>	<b>Description</b>
<i>Surface Flammability</i>	
ASTM D635	Burn rate test
ASTM E84	Tunnel test
ASTM E162	Radiant Panel
ASTM E648	Floor radiant panel
FED-STD-501, Method 6411	Floor covering, fire resistance
UL 94	Flammability of plastics
<i>Vertical Flame Resistance</i>	
ASTM D6413*	Flame Resistance of textiles
<i>Smoke Generation</i>	
ASTM E84	Tunnel test
ASTM E662	Specific optical density of smoke
<i>Test for incombustibility</i>	
46 CFR 164.009	Heated tube test
<i>Fire endurance</i>	
NFPA 267**	Fire characteristics of mattresses
UL 1709**	Hydrocarbon pool fire exposure test

\* A minimum of five specimens from each of the warp and fill directions on materials of the same lot shall be tested and their results averaged (arithmetic mean).

\*\* Only one specimen.

The significance of this work is that the identification of non-metallic materials with improved fire and flammability properties will reduce the fire risk associated with their use on naval vessels. Although no small scale test (or tests) can be used to fully evaluate how materials will react in a fire, the tests can be used to compare the performance of materials under the test conditions. The results of small scale tests are also used as input for fire models that predict fire development in a space. Fire models continue to evolve and as computing power (and speed) increases, the ability to evaluate the contribution of materials to the development and severity of fires in ship board spaces will increase. Models can also be used to study the effect of design on the time it takes crew to exit a burning or damaged ship and its compartments.

## 2.2 Fire/Damage Sensors and Systems

Volume sensors differ from the more traditional point fire sensors in that they have the ability to monitor a space for indications of the presence of fire or damage even when the fire or damage is distant from the sensor. The ability to monitor a space for fire and damage is important because early detection allows damage control personnel to address the situation in a timely manner and reduces the chance that fire or damage will spread from the initiation site. It is also important that sensor systems be designed to minimize false alarms arising from nuisance events. The minimization of false alarms is critical because false alarms lead to the operator losing confidence in the sensing system. This can result in real fire and damage events being ignored on the ship or the system being turned off. In either case this severely compromises ship safety.

A Canadian Demonstrator Prototype (CDP) volume sensor system (VSS) was acquired and evaluated [2,3]. It is an improved version of the VSS developed by the US Naval Research Laboratory (NRL) as part of the Damage Control - Automation for Reduced Manning (DC-ARM) program. A schematic of the system is shown in Figure 1. The VSS combines multiple sensors with local pre-processing and off-device data fusion to synthesize the discrete inputs and generate casualty alarm signals.

The system includes color closed circuit television (CCTV) imaging, monochrome long wavelength video (LWVD) imaging, three single-element (non-imaging) narrow-band spectral sensors and a microphone for acoustic (ACST) sensing. These sensors are incorporated into a single sensing unit. The unit is shown in Figure 2. The LWVD includes a cut off filter to reduce confounding signals by removing visible wavelengths. The narrow-band sensors operate at ultraviolet (UV), infrared (IR) and near infrared (NIR) wavelengths and are collectively referred to as the Spectral-Based Volume Sensor (SBVS).

The VSS has algorithms to pre-process the raw signals in order to reduce the amount of data transmitted from the sensor head to the control computers. Machine vision systems are used to evaluate the imager outputs to identify smoke, fire and other events of interest.

The performance of the CDP VSS was evaluated during fire testing of a magazine space mock-up on the NRL fire test platform, the ex-USS SHADWELL, in September 2010. The purpose of the tests was to establish the sensitivity of the CDP system with regard to the identification of various fires, nuisance sources, pipe ruptures and environmental conditions that might take place onboard ships and to identify operational limitations of the CDP VSS.

The results of the tests are shown in Table 2. The CDP VSS was able to detect 100% of the in-space fires and large (710 kW) adjacent space spray fires (the latter due to charring of paint within the magazine space). It was not able to detect the small (100 kW) external spray fire in an adjacent space. This was because the fire had relatively little impact on conditions within the test space due to the insulation on the bulkhead. Detection times for smoldering (cable) fires were much longer than for flaming fires due to the prolonged delay before flaming combustion was initiated.

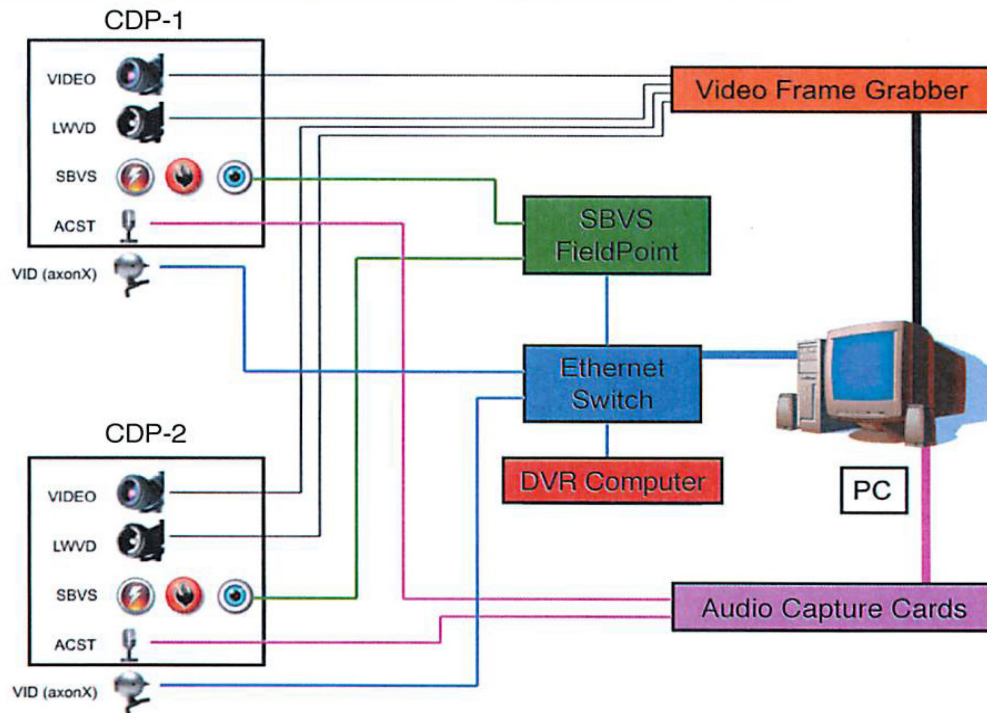


Figure 1- Schematic of the Canadian Demonstrator Prototype – Volume Sensor Sensor.

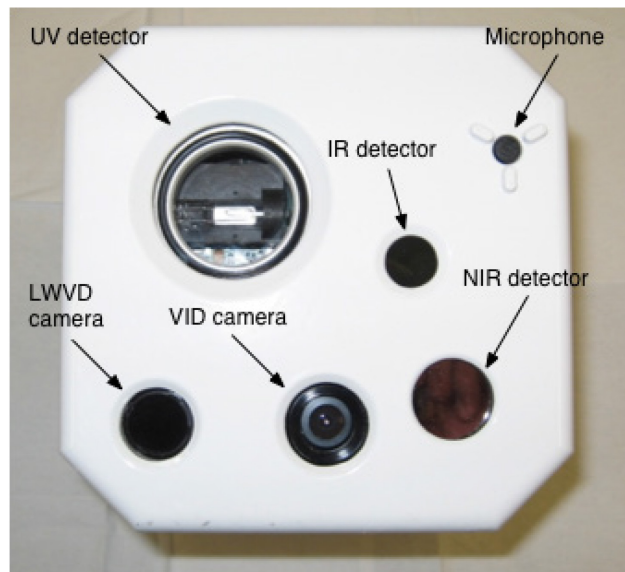


Figure 2 - Sensor head unit of the Canadian Demonstrator Prototype – Volume Sensor Sensor.

Detection times were highly variable, even for fires of the same type and size. For crib fires, there were enough different fire sizes and replicates of each size to permit some statistical analysis. The analysis indicated that there was no correlation between fire size and detection

times. The lack of correlation implies that fire size did not critically affect detection times. The large standard deviations for each fire size also suggest that factors such as fire location and random ventilation effects were important.

There were more false alarms than expected during the tests; this was attributed to the effects of quartz lighting. The VS cameras have fixed gain and exposure settings and, as a result, the intense, focused light from the quartz lights caused large overexposed regions in the images. The axonX Signifire cameras use automatic gain and exposure, but the lighting forced them to stop down their exposure settings so that the majority of the test compartment was too dark for accurate smoke detection. Some of the false flame alarms were likely caused by unusually bright reflections due to the quartz work lights, both installed and portable, used in the test space instead of Navy-standard fluorescent lights.

*Table 2 - Summary of the detection of fire tests on the ex-USS SHADWELL by the Canadian Demonstrator Prototype – Volume Sensor System.*

Summary of Fire Detections				
Location	Category	Category	Detection/ Tests	Max. AlarmTime (s)
In-Space	Smoldering	Cable	4/4	666
	Flaming	25 kW Crib	2/2	34
		50 kW Crib	4/4	231
		75 kW Crib	3/3	137
		100 kW Crib	6/6	126
		250 kW Crib	2/2	109
		100 Pool	1/1	14
Adjacent Space	Flaming	100 kW Spray	0/1	
		710 kW Spray	3/3	200

There were four non-fire casualty tests in which hose and pipe ruptures were simulated. Both of the water leaks were detected but two simulated air leaks were not. Flame alarms were triggered in three out of eight (38%) of the non-casualty tests.

Dynalec combined ionization (flame) and photoelectric (smoke) detectors were installed in the overhead of the test space and the alarm times for the CDP and Dynalec systems compared. The CDP performance was comparable to that of the Dynalec system but the latter has no capability for non-fire/smoke casualties.

The CDP VSS is available for further testing and evaluation. Opportunities to trial the system on an operational ship will be pursued.

## **2.3 Condition Based Monitoring (CBM) Sensors and Systems**

This activity focused on the development of a CBM system with the capability to provide a real-time assessment of a ship's entire charge of oil to shipboard personnel or the life cycle equipment manager [4-7]. This information facilitates a proactive approach to predicting and troubleshooting potential lubricating oil problems. Real-time assessment of critical lubricant properties will allow operators to replace the lubricant based on requirement, as opposed to time based replacement which is the current practice for changing the lubricating oil. It may also provide shipboard personnel with evidence indicating a mechanical problem with the engine (i.e., bearing deterioration) prior to catastrophic failure of the component.

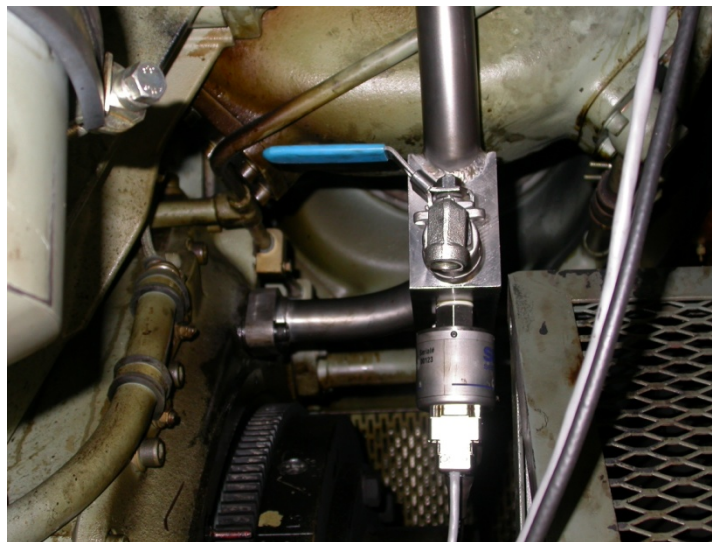
A prototype integrated electronics suite for monitoring the lubricant quality in an 850 kW MWM diesel generator was designed and installed onboard HMCS ST. JOHN'S for an extended duration trial. The purpose of the trial was to test the prototype system in service and validate the results generated by the system with those obtained from the laboratory analysis of oil samples taken during the trial. The system monitored the temperature, viscosity, and general quality (dielectric) of the oil returning to the engine block, from one of the two turbo-blowers installed on the engine. The system was configured to provide both a digital display of the various process variables to shipboard personnel and to store the data associated with each process variable for subsequent post processing by DRDC. Once activated, the system was self supervising and reinitialized itself in the event of a power interruption to the hardware. The system acquired data throughout the trial but oil samples, requested to allow verification of the sensor data following the shipboard trial, were not taken by the ship's crew. A second ship board trial was requested.

The second shipboard evaluation of a CBM system was started onboard HMCS ST. JOHN'S during the latter half of 2011. The latest CBM system is less intrusive and has an improved graphical user interface (GUI) and plumbing to facilitate the collection of oil samples for laboratory verification of the system results following the trial. The CBM system is shown in Figure 3 and installed on an 850 kW MWM diesel generator on HMCS ST. JOHN'S in Figure 4. The sensor suite consists of third generation sensors that will monitor temperature, viscosity, dielectric constant and conductivity of the oil returning to the block from the turbo-blower.

The data collection/display incorporates a ruggedized miniature tablet computer mounted in the front of the power supply. The use of this computer allows the data to be displayed using a custom designed user friendly GUI. The graphical user interface display is shown in Figure 5. The mini tablet computer will also store all acquired data making the installation of a data logger unnecessary. An oil sampling valve has also been added to accommodate the frequent acquisition of oil samples from the running system to verify sensor data.



*Figure 3 - Diesel lubricating oil condition based monitoring sensor unit. The two sensors are located below the steel block, an AnaloxRS temperature and dielectric constant sensor on the left and a Sengenuity FCS temperature, viscosity, dielectric constant and conductivity sensor on the right.*



*Figure 4- Diesel lubricating oil condition based monitoring sensor unit in place on a 850 kW MWM diesel generator on HMCS ST. JOHN'S.*



*Figure 5 - Graphical user interface (GUI) for the diesel lubricating oil condition based monitoring unit.*

## **2.4 Fire Suppression Systems for Halon Replacement**

Halon based total flooding fire suppression systems will not be used on new build Canadian naval vessels. Halons deplete ozone and this resulted in the ban of production of Halons. Water mist fire suppression systems are one of the alternatives to Halon based systems that may be used. Water mist is non-toxic, does not harm the environment, and water mist systems are low-cost and produce little water damage compared to conventional sprinkler systems. Numerical analysis tools that can predict the effectiveness of water mist systems are desirable as they can provide knowledge of how a particular system and its set up will perform against fire scenarios without having to run expensive large scale tests.

In this work breakdown element, the applicability of modeling to the prediction of the effectiveness of water mist fire suppression was investigated [8-10].

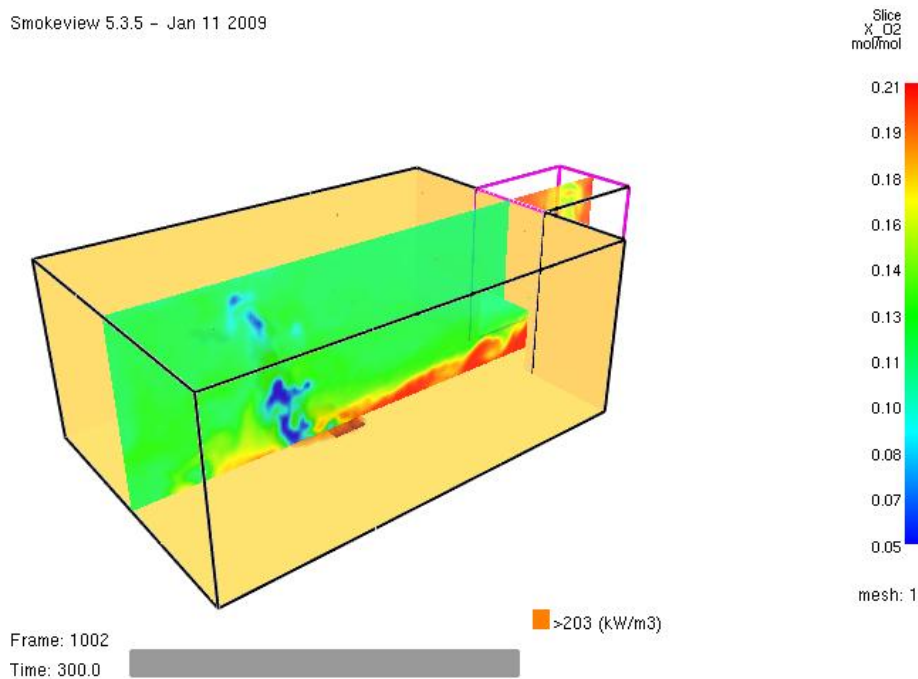
The first report [8] presents a comprehensive review of numerical models for the prediction of water mist fire suppression in ship compartments, details of using computational fluid dynamics tools for such problems, implementation of a one zone model in a computer program, and efforts to validate the numerical models.

The water mist fire suppression models reviewed included one and two zone models and computational fluid dynamics models. Several key deficiencies in simple zone models were identified. Investigations were conducted to outline the input parameters required when simulating water mist fire suppression with two computational fluid dynamics (CFD) packages, Fire Dynamics Simulator 5.3 and CFX 11.0. A test case representative of a ship compartment fire was selected to assess the performance of each of these tools in producing a reasonable answer at an acceptable computational cost. These tools illustrated physical processes that were not represented in simpler models such as ventilation feeding of a fire in a compartment with what would be predicted by a one or two zone model as insufficient oxygen for combustion.



Ventilation feeding of a fire is illustrated in Figure 6 using the Fire Dynamics Simulator CFD Model. However, the simulations required several hours to several days of computational run time.

The Li and Chow zone model [11] was selected for implementation in a computer code named the Water Mist Fire Suppression Utility. The effect of heat release rate, water mist droplet size, and water mist mass flow rate on the model output was assessed. The model generated solutions in a few minutes and its output was compared to results from 21 scenarios for compartment fire suppression. Predictions of fire suppression times were in keeping with those reported for other zone models. However, the predicted fire suppression times from this zone model were significantly shorter than those predicted by the CFD analysis. The extinguishment time predictions of the Li and Chow, Vaari, Wighus and Back zone models and FDS CFD model for the Vaari fire test scenario are shown in Table 3.



*Figure 6 - Oxygen concentration (300 s) for the Vaari scenario calculated using FDS. Ventilation feeding of the fire is indicated by the red colour (high oxygen concentration) that runs from the door to the seat of the fire.*

The second report [9] describes an investigation of the use of a CFD model for fire suppression predictions. It was aimed at improving our understanding of the capabilities of CFD models for predicting water mist fire suppression system (WMFS) performance. Twelve experimentally investigated naval machinery space fire tests were simulated using Fire Dynamics Simulator (FDS) version 5.3.4. Reasonable agreement between the fire test results and those predicted by the FDS CFD model was achieved, but the effort was hampered by a lack of data describing the test configurations and conditions. Data requirements for future experimental work used to validate CFD models and limitations of the FDS version 5.3.4 model were outlined.



Table 3 - Vaari Test Scenario Fire Suppression Times

MODEL	TIME TO FIRE SUPPRESSION (s)	COMPARTMENT TEMPERATURE ( $^{\circ}\text{C}$ )	PARAMETERS USED
LI AND CHOW 1-ZONE	134	76	$[\text{O}_2]_{\text{ext}} = 0.14$ , $h_{\text{wall}} = 0 \text{ Wm}^{-2}\text{K}^{-1}$
LI AND CHOW 1-ZONE	149	71	$[\text{O}_2]_{\text{ext}} = 0.14$ , $h_{\text{wall}} = 30 \text{ Wm}^{-2}\text{K}^{-1}$
LI AND CHOW 1-ZONE	224	64	$[\text{O}_2]_{\text{ext}} = 0.13$ , $h_{\text{wall}} = 100 \text{ Wm}^{-2}\text{K}^{-1}$
VARRI 1-ZONE*	$\approx 135$	$\approx 70$	Unknown
WIGHUS ET. AL. 1-ZONE*	$\approx 200$	$\approx 145$	Unknown
BACK ET. AL. 1-ZONE*	$\approx 125$	$\approx 85$	Unknown
FDS CFD	na	55-220, 875 in plume	Fire not suppressed, values for 300 s
FDS CFD	278	67-200	Wall obstructions added between fire and door

$[\text{O}_2]_{\text{ext}}$  = suppression concentration threshold,  $h_{\text{wall}}$  = heat transfer coefficient of walls

\*Vaari, Jukka, “Modeling of Water Mist Fire Suppression”, *International Water Mist Association*. [www.iwma.net](http://www.iwma.net).

The machinery space test scenario detailed in the International Marine Organization MSC 1165 standard was chosen to systematically study WMFS system parameters. The effect of varying fire size and location, preburn time, the presence of obstructions, mist flow rate, droplet size and velocity distributions, vent size and locations, nozzle placement, and compartment scale were investigated. The influence of scenario parameters are highly dependent upon the compartment configuration, but in general fire size and water flow rate are the most significant parameters followed by the fire and vent locations.

The third report [10] describes the use of Fire Dynamics Simulator (FDS) version 5.5.3 revision 7031 to simulate WMFS system performance for seven experimental test scenarios. This included tests to verify the ability of FDS to adequately capture the buoyancy effects of the fire on the water mist, and to model the ability of WMFS system to extinguish spray fires using variants of the International Marine Organization (IMO) WMFS standard test for machinery spaces and pool fires in representative machinery compartments.

Alterations to the FDS extinction model to account for autoignition and flash-point properties of liquid fuels resulted in improvements to the extinction predictions for WMFS systems. Further refinement of the extinction model is required to predict complete fire suppression and eliminate non-physical fire ignition in low energy regions away from the primary fire.

## 2.5 Novel Fire and Damage Tolerant Materials

A range of organic (carbon-based) materials, most of them polymers, are used on CF vessels. These materials include coatings (paints), electrical and communication cable sheathing, thermal and acoustic insulation, furnishing, bedding, mattresses, flooring, and wood fibre (paper and cardboard) and plastic packaging materials. Coatings provide corrosion protection; polymeric electric and communication cable sheathings are non-conductive and provide insulation against electric shock and shorts; foamed polymers are used for thermal and sound insulation, and furnishings and bedding are used for their comfort and warmth. Although the use of composites has not been prominent on CF ships, requirements for the reduction of weight or radar signature may result in an increase in their use on new vessels.

All organic materials will burn. From a fire and flammability perspective the best approach is to limit the use of flammable materials on ships. However, many of these materials are used because they have unique properties that cannot be provided by other materials or alternative materials with improved fire and flammability properties are so expensive that they are cost prohibitive to use.

*Table 4 - Cone calorimetry results for polyureas synthesized using either phosphorus diol diisocyanate, amine terminated dimethylsiloxane, or both.*

Sample ID	Time to Ignition (s)	Peak Heat Release Rate (kW/m <sup>2</sup> )	Average Heat Release Rate (kW/m <sup>2</sup> )	Total Smoke (m <sup>2</sup> )	Smoke Factor (× 10 <sup>3</sup> kW/kg)	Peak Mass Loss Rate (g/m <sup>2</sup> s)
MIL STD 2031	150	60	n/a	n/a	6.5	n/a
Base polyurea (no phosphorous or polysiloxane)*	21	1252.0	237.4	17.2	657	43.89
Base polyurea (containing 15% of phosphorous polyol in component B)*	21	760.6	310.0	28.3	474	33.56
P2P1S1	11	286.3	133.0	27.2	256	21.14
P2P1S2	14	542.4	144.3	21.8	433	23.11
P2P1S3	16	351.9	69.8	9.1	245	22.95

P2P1S1 - phosphorous diol used to prepare diisocyanate prepolymer (component A)

P2P1S2 - amine terminated dimethyl siloxane used (component B)

P2P1S3 - both phosphorous diol and amine terminated dimethyl siloxane used

There are several approaches to minimizing the fire hazards involved with the use of organic materials on ships. These include the selection of materials that are inherently safer, that is, less susceptible to fire, the chemical modification of the material to improve its fire performance, the use of additives such as flame retardants that improve the performance of a material in a fire, and the protection of the flammable substrate with a non-combustible material that physically separates it from sources of heat and flame [12].

DRDC Atlantic is evaluating polyurea coatings for use in enclosed spaces as damage control materials. For such applications, their fire resistant properties need to be improved. In [13], three base polyurea formulations were developed and evaluated by cone calorimetry. The goal was to replace portions of the organic polyurea backbone to improve the flame retardancy. The first sample utilized a diisocyanate prepolymer with a portion of its backbone made up of a phosphorous polyol, the second sample replaced a portion of the polyether amine with an amine terminated polydimethylsiloxane and the third sample combined the phosphorous polyol with the amine terminated polydimethylsiloxane. Cone calorimetry determined that the third sample yielded the best results for lowering smoke production and increasing time to ignition. The results of the analysis are shown in Table 4. It is believed that the phosphorous polyol and polydimethylsiloxane have a synergistic effect in improving the flame properties. The phosphorous polyol/polydimethylsiloxane based polyurea was then used as the base formulation and various combinations of flame retardant additives were incorporated in an attempt to further improve the flame properties. Cone calorimetry indicated that the best combinations included sodium phosphate, ammonium polyphosphate (APP)/triisocyanurate 3:1, treated graphite, urea, zeolite and melamine.

In [14], various synthetic and additive routes were explored in an effort to further improve the polyurea flame retardancy. The effect of the aromatic content of the polyurea backbone on char formation was investigated. Polyureas utilizing combinations of two aromatic isocyanates and two aromatic amines were produced. Cone calorimetry results indicated that increasing the aromatic content of the polymer backbone resulted in improved flammability properties. Moreover, the addition of char promoting fillers, in the form of expandable graphite, at two different loading levels was explored. Cone calorimetry data indicated that the large particle graphite at a 22% w/w loading level yielded the best results. Even with a modified backbone, and char promoting filler, the polyurea did not meet the requirement (DoD Military Specification for Standard fire and toxicity test methods and qualification procedure for composite material systems used in hull, machinery and structural applications (MIL-STD-2031)) of 150 seconds time to ignition. To increase the time to ignition two different barrier coatings were applied to the surface of the polyurea. It was found that the time to ignition, peak Heat Release Rate (HRR) and total smoke all improved with the coating when compared to uncoated samples.

In [15], the use of three ignition barrier coatings was investigated in an attempt to increase the time to ignition of polyurea substrates. An original polyurea and an aromatic base formulation that performed well in previous work [14] were used. Graphite was also added to the ignition barrier coatings in an attempt to improve the time to ignition. It was found that the flammability properties including time to ignition, peak heat release rate and total smoke of polyureas with the ignition barrier coating improved compared to uncoated polyureas. The best cone calorimetry results were obtained from a gypsum-based ignition barrier paint containing graphite. When the

graphite was added to this barrier coating, significant improvements were observed over samples not containing graphite. This was not seen in the other barrier systems that were investigated. The gypsum and graphite may be working synergistically to improve the flame properties. With the addition of graphite, this system met all specifications of MIL STD 2031, on both the original polyurea and the aromatic polyurea.

## **2.6 New Technologies and Materials for Enhanced Damage and Fire Tolerance of Naval Vessels**

New fire and damage control technologies and approaches to minimizing hazards associated with non-metallic materials on naval vessels were reviewed in Reference [12]. The technologies and topics discussed included advances in point and volume fire and damage sensors and systems, smoke control (ejection) systems, smart valves, water mist and gaseous agent fire suppression systems, and aerosol fire extinguishing agents. Technology readiness levels (TRL) of these technologies are assigned based on the criteria developed by the United States Department of Defence. In many instances the components of systems, for instance the detectors used in point and volume sensors, have already been used on naval vessels. However, their incorporation into fire and damage control systems has not progressed past the prototype/demonstrator phase.

Approaches to enhancing the fire and flammability properties of non-metallic (polymeric) materials used on naval vessels were also reviewed. The approaches include the selection of polymeric materials with inherent fire resistance, the use of flame retardant additives including nanoparticles, the incorporation of molecules into the polymer backbone that have flame retardant properties, and the use of intumescent coatings to protect the underlying substrate. Finally, standards and test methods used to evaluate the fire performance of non-metallic materials were discussed.

The technologies reviewed have the potential to not only enhance fire and damage control on naval vessels but also to automate certain fire and damage control tasks presently carried out by crew members. Materials with improved fire tolerance will reduce the risk associated with their use on board naval vessels. Materials that are more difficult to ignite and release less heat, smoke and toxic gases contribute to improved fire safety.

## **3 Conclusions**

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This ARP investigated developments in systems for the detection of ship board fire and damage events and the real time monitoring of machinery lubricating oil. Should new build ships have reduced crewing levels, these technologies will aid in reducing the tasks that have to be done by crew members with respect to fire/damage control monitoring and machinery lubricating oil monitoring. If crewing levels are not reduced, these technologies will enhance fire/damage detection and machinery monitoring capabilities.

The ability to accurately model water mist fire suppression systems will aid in determining the effectiveness of these systems in a range of fire scenarios and aid in the selection of a system design that is best suited for fires in a particular shipboard space. The review of modeling

indicated the importance of acquiring as much data as is possible from full scale fire tests. This data can then be used to validate and verify the modeling predictions.

Non-metallic materials will be used on naval vessels for a number of applications. As they are all flammable, it is very important that the materials required and/or selected for a particular application contribute as little as is possible to the fire load on a vessel. Approaches to reducing ignitability, heat release, and smoke are therefore very important. In addition, tests that can rank the flammability properties of materials will ensure that the 'safest' materials are used on naval vessels.

## **4 The Way Ahead and Future Work**

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The Canadian Demonstrator Prototype volume sensor system (CDP-VSS) has been loaned to DMSS 4-2 for further evaluation. The work will be done at the University of Waterloo in the Department of Mechanical Engineering. Prior to a shipboard trial, the CDP-VSS will have to be hardened for shock, blast, and fire. The interface between the system and the operator may also have to be optimized to ensure that it gives the operator the information he or she needs to effectively address fire and damage control events.

The CBM sensor suite continues to be evaluated on an operational CPF (HMCS ST. JOHN'S) auxiliary diesel engine. This work is focussed on correlating the data from the sensor suite with the results from laboratory testing of oil samples taken over a period of time from the same system that the sensor suite is monitoring. The results will be used to select sensors that give the most reliable real time, on line information about the oil used in a particular piece of machinery.

DRDC Atlantic, Dockyard Laboratory (Atlantic) is participating in a Project Arrangement under the Canada/Netherlands/Sweden COOPERATIVE SCIENCE AND TECHNOLOGY Memorandum of Understanding on New Technologies for Fire Suppression OnBoard Naval Craft (FiST). This project will continue investigations of the use and effectiveness of water mist systems on ships and submarines. It will also investigate the use of modeling of water mist fire suppression. Other topics to be addressed are the use of portable and handheld fire extinguishing technologies such as propelled extinguishing agents (aerosols, compressed air foam systems, cutting extinguishers, and cool gas generator technology). The project will involve fire testing of damaged water mist systems and testing of the applicability of water mist systems for fire suppression in magazine spaces.

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## Annex A Acceptance Criteria for Fire Test Methods

Test	Description	Criteria	Test Method
Oxygen-Temperature Index (%)	The minimum concentration of oxygen in a flowing oxygen nitrogen mixture capable of supporting flaming combustion of a material	Minimum % oxygen @ 25°C 35% % oxygen @ 75°C 30% % oxygen @ 300°C 21%	ASTM D 2863 (modified)
Flame Spread Index	A number or classification indicating a comparative measure derived from observations made during the progress of the boundary of a zone of flame under defined test conditions	Maximum 20	ASTM E 162
Ignitability (Seconds)	The ease of ignition, as measured by the time to ignite in seconds, at a specified heat flux	<i>Minimum</i> 100 kW/m <sup>2</sup> Flux 60 75 kW/m <sup>2</sup> Flux 90 50 kW/m <sup>2</sup> Flux 150 25 kW/m <sup>2</sup> Flux 300	ASTM E 1354
Heat Release Rate (kW/m <sup>2</sup> )	Heat produced by a material, expressed per unit of exposed surface per unit of time.	<i>Maximum</i> <b>100 kW/m<sup>2</sup> Flux</b> Peak 150 Average 300 secs 120 <b>75 kW/m<sup>2</sup> Flux</b> Peak 100 Average 300 secs 100 <b>50 kW/m<sup>2</sup> Flux</b> Peak 65 Average 300 secs 50 <b>25 kW/m<sup>2</sup> Flux</b> Peak 50 Average 300 secs 50	ASTM E 1354
Smoke Obscuration	Reduction of light transmission by smoke as measured by light attenuation	<i>Maximum</i> Ds during 300 secs 100 Dmax occurrence 240 secs	ASTM E 662
Combustion Gas Generation	Rate of production of combustion gases (e.g. CO, CO <sub>2</sub> , HCl, HCn, NOx, SOx, halogen, acid gases and total hydrocarbons	<b>25 kW/m<sup>2</sup> Flux</b> <i>Maximum</i> CO 200 ppm CO <sub>2</sub> 4% (vol) HCN 30 ppm HCl 100 ppm	ASTM E 1354
Burn	Test method to determine the	No burn through in 30	

Test	Description	Criteria	Test Method
Through Fire Test	time for a flame to burn through a composite material system under controlled fire exposure conditions.	minutes	DTRC Burn Through Fire Test
Quarter Scale Fire Test	Test method to determine the flashover potential of materials in a room when subjected to a fire exposure	No flashover in 10 minutes	Navy Procedure
Large Scale Open Environment Test	A method to test materials at full size for their intended application under controlled fire exposure to determine fire tolerance and ease of extinguishment	Pass	Navy Procedure
Large Scale Pressurable Fire Test	Method to test materials using an enclosed compartment in a simulated environment under a controlled fire exposure.	Pass	Navy Procedure
N-Gas Model Toxicity Screening	Test method to determine the potential toxic effects of combustion products (smoke and fire gases) using laboratory rats.	Pass	Navy Procedure

## Annex B Def Standard 07-247 Part 1- Summary of Listed Test methods

Test No.	REFERENCES	PURPOSE OF TEST		DESCRIPTION	
1	<b>BS 476 Part 4</b> Non-combustibility (See also BS EN ISO 1182)	Materials are classified as combustible or non-combustible by identifying those which make little or no thermal contribution to the heat of the furnace and do not produce a flame, and by calling the remainder “combustible”.		Tests carried out in a furnace. The furnace is heated to 750 ±10°C and stabilised for 10 min. The specimen is inserted and the furnace temperature is recorded for a further 20 minutes. The occurrence of any flaming in the furnace is noted.	
<b>Interpretation of Test Data:</b> The material shall be deemed non-combustible if, during the test, none of the three specimens either: (1) Causes the temperature in the furnace to rise by 50°C or more above the initial furnace temperature, or; (2) Is observed to flame continuously for 10s or more inside the furnace. Otherwise, the material shall be deemed combustible.					
2	<b>BS 476 Part 6</b> Fire propagation	The test takes account of the combined effect of factors such as the ignition characteristics, the amount and the rate of heat release, and the thermal properties of the product in relation to their ability to accelerate the rate of fire growth. (Note this test is used in UK building (regulations).)		Test carried out in a combustion chamber. The face of the specimen is subjected to gas jets impinging on the bottom edge of the specimen for 20 min and radiant heat applied 2 min 45 sec after start of test.	
<b>Interpretation of Test Data:</b> The index of performance <b>I</b> is the summation of sub indices I1, I2 and I3 calculated from the funnel gas temperature/time curve. The smaller the index <b>I</b> the more acceptable the material. The value of the sub index I1 is a measure of the heat contribution of the material to the early stages of the fire					
3	<b>BS 476 Part 7</b> Surface spread of flame	The test takes account of the combined effect of factors such as ignition characteristics and the extent to which the flame spreads over the surface of the product under opposed flow conditions. (Note this test is used in UK building regulations.)		Vertically oriented specimens are exposed at right angles to a radiant panel and in addition a pilot flame is applied during the first minute of the test. Observations are made of the time required for the flame front to laterally spread along the specimen to reach a series of reference marks. (Note: A small scale test was specified in earlier versions of this standard and was used in preliminary investigations only. It is no longer included standard.)	
<b>Interpretation of Test Data:</b>					
		<b>Flame spread at 1.5 minute</b>		<b>Final spread of flame</b>	
<b>Classification</b>		<b>Limit mm</b>	<b>Limit for one specimen in sample</b>	<b>Limit (mm)</b>	<b>Limit for one specimen in sample (mm)</b>

Test No.	REFERENCES	PURPOSE OF TEST		DESCRIPTION	
			(mm)		
	Class 1	165	165+25	165	165+25
	Class 2	215	215+25	455	455+45
	Class 3	265	265+25	710	710+76
	Class 4	Exceeding the limits for class 3			
4	<b>BS 476 Part 12</b> Ignitability by direct flame impingement (Supersedes BS 476 Part 5)	To obtain information on the performance of a specimen in the early stages of a fire, by determining the ignitability of materials, composites and assemblies subjected to direct impingement of flames of different size and intensity but without impressed irradiance.		Vertically held specimens are exposed to specified flames of different sizes and intensities and their ignition behaviour observed.	
	<b>Interpretation of Test Data:</b> No acceptance criteria are given but the standard allows specifiers, with experience, to require a product to be tested by a specific ignition source, relevant to the end use application, for a specific flame application time and position.				
5	<b>BS 476 Part 15</b> $\equiv$ <b>ISO 5660 Part 1</b> Rate of heat release	To determine the heat release rates for essentially flat materials, assemblies, etc.		A cone calorimeter which determines heat release rate using the oxygen consumption principle is used to burn specimens in ambient air conditions, while being subjected to a predetermined external irradiance within the range 0-100 kW/m <sup>2</sup> .	
	<b>Interpretation of Test Data:</b> This test procedure provides a considerable amount of information including data on rate of heat release, mass loss rate, time to ignition and effective heat of combustion. Using additional procedures/ apparatus, that are generally fitted as standard on most instruments, data on rates of production of smoke, CO and CO <sub>2</sub> are also collected. No acceptance criteria are given in the standard, so at present the information can be used for direct comparison of materials only. As experience is ‘built-up’, performance requirements, for material types or applications, will be set.				
6	<b>BS 2316 Parts 1 &amp; 2</b> Specification for radio frequency cables Flammability test for cables (Part 1, Clause 6.7)	To check that cables will not support combustion or propagate flame.		Specimen cables are supported at an angle of 45° in a draught free chamber. The hottest point of a flame is arranged to impinge on the central position of the specimen for 15 seconds. Observations are made on any flaming debris, time to cessation of burning and length of burn.	
	<b>Interpretation of Test Data:</b> The material shall be deemed acceptable if no flaming particles fall from the specimen, the cable ceases to burn within a specified time, and total burn length or char does not exceed 75 mm or fourteen times the nominal diameter of the cable, whichever is the greatest.				
7	<b>BS EN ISO 4589 Part 2</b> Oxygen index (ambient temperature test)	To determine the relative flammability of materials by comparing the lowest level of O <sub>2</sub> in a mixture of O <sub>2</sub> and N <sub>2</sub> at which combustion of a material is		Specimens are supported vertically in a glass chimney through which passes a controlled mixture of O <sub>2</sub> and N <sub>2</sub> constant flow rate. By testing a series of specimens at	

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
		just supported at ambient temperature, under specified conditions.	different oxygen concentrations, the Oxygen Index is determined as the minimum oxygen concentration that will support combustion of a specimen over a short specified time and/or distance.
	<p><b>Interpretation of Test Data:</b> The oxygen index <b>OI</b> is calculated as the percentage volume of oxygen in the critical mixture.</p> $\text{Oxygen Index} = \frac{(100) \times (O_2)}{(O_2) + (N_2)}$ <p>Where O<sub>2</sub> and N<sub>2</sub> are the volumetric flow rates of oxygen and nitrogen respectively. The higher the index <b>OI</b> the more acceptable the material.</p>		
8	<p><b>BS EN ISO 4589 Part 3 Annex A</b></p> <p>Flammability temperature (FT)</p>	To determine the relative flammability of materials by comparing the lowest temperature at which combustion of a material is just supported in air, under specified conditions.	Specimens are supported vertically in a glass chimney through which passes preheated air at a constant flow rate. By testing a series of specimens at different temperatures, the Flammability Temperature (FT) is determined as the minimum elevated temperature that will support combustion of a specimen over a short specified time and/or distance. (Note: This is effectively the temperature at which the OI of the material falls to 20.9 (the oxygen content of air at 23 ± 2°C).
	<p><b>Interpretation of Test Data:</b> The higher the Flammability Temperature (FT) the more acceptable the material. (Note: This test property was previously described as "Temperature Index" and was specified in NES 715 (see Table 2 Test 42). In this context the terms "Temperature Index" and "Flammability Temperature" have the same meaning, although users should note that where the ISO version of the test specifies different specimen dimensions (e.g. for foams) the results may not be comparable.)</p>		
9	<p><b>BS 4735</b> Horizontal burning characteristics of cellular plastic and cellular rubber materials (foams)</p>	To compare the horizontal burning characteristics of cellular plastics and cellular rubber materials when subjected to a small flame. The results can be of value in controlling manufacturing processes to ensure consistency of production. There is no known evidence of correlation between the results of such tests and burning under actual use conditions. Therefore conclusions cannot and shall not be drawn from such results regarding burning behaviour under actual	Conducted in a test chamber within a fume cupboard. The specimen is supported on a gauze holder and subjected to a gas flame, 13 mm below the gauze, for a period of 60 sec. The extent and time of burning and mass loss, if required, are recorded. Any warping, charring, melting or dripping of the specimen is to be timed and recorded together with any inclination to produce flaming droplets.

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
		use conditions.	
	<b>Interpretation of Test Data:</b> The resulting time and observations are used to compare the horizontal burning characteristics of cellular foams, such as could be subjected to the effects of a lighted cigarette or similar.		
<b>10</b>	<b>BS 4790</b> Flammability of textile floor coverings (hot metal nut method)	To determine spread of flame, after-glow and smouldering in carpets, etc.	A Stainless steel nut mass 30g heated to 900°C applied centre of specimen for 30 seconds. The time in seconds from application of the nut and to extinction of any flames, of any afterglow and/or smouldering are measured. Where the effects of ignition reach the clamping ring (125mm internal radius) the time in seconds is also noted.
	<b>Interpretation of Test Data:</b> The resulting time and distance data are used to compare the flammability characteristics of competing textile floor coverings in accordance with <b>BS 5287</b>		
<b>11</b>	<b>BS 5287</b> Assessment and labelling of textile floor coverings tested to <b>BS 4790</b>	To classify the results obtained by test to <b>BS 4790</b>	Three classifications are given: <b>1.</b> Affected area up to 35 mm -low radius of effects of ignition <b>2.</b> affected area between 35 and 75 mm -medium radius of effects of ignition <b>3.</b> Affected area 75 mm or more - high radius of effects of ignition
	<b>Interpretation of Test Data:</b> Classification 1 is the best and 3 the worst.		
<b>12</b>	<b>BS 5438</b> Flammability of vertically oriented textile fabrics and fabric assemblies subjected to small igniting flame (Partially replaced by BS EN 532, BS EN ISO 6940 and BS EN ISO 6941)	To observe and measure aspects of the flammability of vertically oriented textile fabrics in a single layer or more. This test may also be called up after the material has undergone repeated washing (see BS EN 1102) to ensure durability of FR treatments.	Vertical strip test for textile fabrics. Facts reported are : Time to strip threads severance; Separation of any flaming debris; Duration of flaming; Duration of afterglow.
	<b>Interpretation of Test Data:</b> Characteristics determined are Ignition Time, Spread of Flame and Rate of Flame Spread.		
<b>13</b>	<b>BS 5946</b> Punking behaviour of phenol-formaldehyde foam	To assess the resistance of phenol-formaldehyde foam to propagation of slow combustion (known as “Punking”) initiated by localised application of a source of heat	A sample of foam is heated using a Bunsen burner until a measured temperature of 180°C is reached. The Bunsen burner is removed and temperature recorded.

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
		once the heat source has been removed.	
	<b>Interpretation of Test Data:</b> An increase in temperature beyond 360°C indicates that the foam exhibits punking behaviour. A fall in temperature below 100°C indicates that the foam is non-punking.		
14	<b>BS EN 50267 Parts 1 and 2-1</b> Halogen acid gases evolved during combustion of cable materials (Formerly BS 6425 Part 1)	Determination of amount of halogen acid gas evolved during combustion of cables.	0.5g to 1g of a sample is placed into a combustion boat which is inserted into a combustion tube in the furnace hot zone. The combustion tube is connected to wash bottles and the sample temperature is raised to 800°C at a rate of 20°C/min and held for 20 minutes. By analysis of the wash bottles the halogen acid content can be found.
	<b>Interpretation of Test Data:</b> The lower the amount of halogen acid expressed as milligrams of hydrochloric per gram the more acceptable the material.		
15	<b>BS 3G 230 Test 28 (a)</b> Flammability - Method 1 (Formerly BS 2G 230)	To observe and measure aspects of the flammability of cables.	A 900 mm length of the sample is mounted at 60° and a flame applied 200 mm from the bottom clamp. The duration of flame application depends on the size and type of cable being tested. Observations of flaming debris, time to cessation of burning and length of burning and length of burnt or charred material measured.
	<b>Interpretation of Test Data:</b> During the test no flaming particles shall fall from the specimen. Burning shall cease within 3 seconds and total length burned or charred shall not exceed 75 mm. (Note BS 2G 230 has been superseded by BS 3G 230 and for Test 28(a) the requirement for burning to cease has been revised to 3 seconds. However, this test, with its original 15 second limit, is called up as BS 2G 230 in Def Stan 61-12 Part 0 Clause 13.39)		
16	<b>BS 3G 230 Test 28 (b)</b> Flammability - Method 2 (Formerly BS 2G 230) (Note: Def Stan 61-12 Part 0 Clause 13.40 refers to this tests as “Flame Propagation”)	Assessment of propagation of flame on a vertical cable with sheath removed on its lower portion.	Using the same chamber as BS 3G 230 Test 28(a). 50 mm of insulation is removed from one end of a 450 mm long sample which is then placed vertically in the flame of a Bunsen burner. A record is made of the burn length and the time of burning after the removal of the flame.
	<b>Interpretation of Test Data:</b> No flaming particles shall fall from the specimen. Burning shall cease within 15 seconds and burn and char length shall not exceed 90 mm. (Note. BS 2G 230 has been superseded by BS 3G 230, although there are no substantive changes to the requirement.)		

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
17	<b>DOT Information Sheet FP/1989 Annex</b>	Determination of flammability of carpets and carpet underlays.	A specimen with its top surface facing down is placed on a metal tripod so that the height of this surface is 8 mm below the top of the gas flame. The gas flame is applied at right angles to the plane of the specimen at its centre and then when all flaming has ceased and the specimen temperature has returned to normal at the edge.
	<b>Interpretation of Test Data:</b> Time and extinction of any flaming is recorded. The shorter the time the more acceptable the material.		
18	<b>Def Stan 02-137</b> PU foam components for mattresses, cushions and upholstery Fire resistance test	To assess the fire resistance of composite components: (1) Core foam wrapped in barrier foam (2) Barrier foam wrapped in cotton cover	(1) 4 x No 6 cribs placed in centre of sample to form a square with sides touching and ignite. (2) 4 x No 7 cribs placed in centre of sample to form a square with sides touching and ignite. In each test the following observations are made (a) Time to cessation of flaming, smoking and glowing of barrier foam (b) The integrity of the barrier foam char.
	<b>Interpretation of Test Data:</b> The resulting times and integrity of char are used to compare the fire resistance of the components. Alternatively a specific time could be set by which cessation is achieved for acceptance of components.		
19	<b>Def Stan 02-345</b> Flexible rubber pipe assemblies and bellows Flame Test	To assess the fire resistance of flexible pipe assemblies	A flame from a butane gas torch is directed onto a vibrating hose, end fitting, bend or bellows for 15 minutes. Damage is to be observed
	<b>Interpretation of Test Data:</b> An assembly will be deemed to have failed if leakage occurs within a specified time.		
20	<b>Def Stan 02-641</b> Vertical flammability of electric cables	Determination of the vertical flammability of electric cables.	850 mm long test specimen consisting of a single cable or a number of cables twisted together is mounted vertically in a stainless steel tube inside a draught free enclosure over a conical fuel tray. Once all the fuel has been consumed the test specimen is allowed to continue to burn until all burning and glowing has ceased. Specimen is then held horizontally 300 mm above floor and allowed to fall. Damage length is measured.
	<b>Interpretation of Test Data:</b> The shorter the damage length the more acceptable the material.		
21	<b>Def Stan 02-711</b>	To evaluate the density of smoke	Specimens are exposed in the



Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
	Smoke Index	(light obscuration) evolved by materials under conditions of fire	vertical orientation to a constant radiant heat source (25 kW/m <sup>2</sup> ), inside a sealed chamber ("NBS smoke chamber"). For the first five minutes exposure is to the radiant heater only. After 5 minutes a multi-jet burner is ignited and runs for up to a further 15 minutes. A photometric system is used to monitor percentage light transmission with respect to time. Values of the specific optical density (DS) of the smoke that accumulates inside the chamber are derived from corrected transmission data.
	<b>Interpretation of Test Data:</b> A Smoke Index is calculated from the average rates of change of DS calculated between the start of the test and up to three transmission reference points (70%, 40%, 10%) and also between the start of the test and the minimum transmission point. The computation of the smoke index ensures that materials producing heavy smoke in a short time receive a higher rating; others giving heavy smoke in a longer time, or only light smoke, are lower rated. The lower the Smoke Index the more acceptable the material.		
22	Def Stan 02-713 Toxicity Index	Measurement of toxic potency of the gases in the products of combustion.	Specimens ~1g are completely burnt inside a sealed chamber using a gas/air burner at 1150°C. The combustion products are then quantitatively analysed for a specified set of gases.
	<b>Interpretation of Test Data:</b> The toxicity index <b>TI</b> is derived from the summation of the individual qualities of gas produced relative to the amount considered to be fatal to humans after 30 min exposure. The lower the Toxicity Index the more acceptable the material.		
23	Def Stan 02-807 Part 1 Welding and burning blankets and hangar fire curtains Flame Cutting Test	To determine the ability of silica fabric blankets to resist molten slag.	A specimen of cloth is held horizontally and a steel plate is mounted above the cloth. A 20 mm wide piece of the steel plate is then flame cut and the molten slag and cut piece are allowed to fall onto the test cloth.
	<b>Interpretation of Test Data:</b> The longer the cloth supports the steel cut-off and prevents penetration of the molten slag, the more acceptable the material.		
24	ISO 5660 Part 1 ≡ BS 476 Part 15 Rate of heat release	To determine the heat release rates for essentially flat materials, assemblies, etc.	A cone calorimeter which determines heat release rate using the oxygen consumption principle is used to burn specimens in ambient air conditions, while being subjected to a predetermined external irradiance within the range 0-100 kW/m <sup>2</sup> .

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
	<b>Interpretation of Test Data:</b> This test procedure provides a considerable amount of information including data on rate of heat release, mass loss rate, time to ignition and effective heat of combustion. Using additional procedures/ apparatus that are generally fitted as standard on most instruments, data on rates of production of smoke CO and CO2 are also collected. No acceptance criteria are given in the standard, so at present the information can be used for direct comparison of materials only. As experience is ‘built-up’, performance requirements, for material types or applications, will be set.		
25	<b>Safety of Life at Sea Regulations - 1974</b> Regulation 3 Fire Resistance	To assess and classify the fire resistance of bulkheads and deck panels.	One side of 4.65 m² specimen is exposed on a furnace to a standard time temperature curve which represents a typical cellulosic fire. Observations are made on passage of smoke and flame (integrity), the temperature rise on the unexposed face (insulation) and the rise in temperature of any structural core.
26	<b>Safety of Life at Sea - 1981 Regulations (SOLAS 1981 Regulations)</b> Class B Panels		
	<b>Interpretation of Test Data:</b> The average temperature of the unexposed side shall not rise more than 139°C above the original temperature, nor will the temperature at one point, including any joint, rise more than a specified amount (Class A 180°C, Class B 225°C) above the original temperature within specified times.  Divisions are given a letter classification according their construction type (Class A - steel or equivalent, Class B approved non-combustible material), plus their time to integrity failure (Class A must retain integrity for 60 minutes; Class B must retain integrity for 30 minutes). In addition they are given a numerical time rating, according to their time to insulation failure e.g. an A-30 rated division might be constructed of steel plate protected with a mineral wool fire insulation material, must retain integrity for 60 minutes and take at least 30 minutes for the average temperature of the unexposed face to reach 139°C above ambient.  (Note: IMO regulations have been brought together into the SOLAS Consolidated Edition, 2004 and the requirements for classification of the fire resistance of bulkheads are set out in Chapter II-2 Regulation 3. The fire resistance test described above is now specified in detail in IMO Resolution A.754(18), published as part of the IMO FTP Code MSC.61(67)). The test is similar to BS 476 Part 20 (test 36 below) and to ISO 834.)		
27	<b>ASTM E 648</b> Critical radiant flux density of floor covering systems	Investigation of the performance of floor coverings	A horizontal specimen is exposed to radiant heat and pilot flame applied at the narrow edge nearest the radiant panel for 10 min and then moved 50 mm above and parallel to the specimen. The test is terminated when any flames are extinguished or if the specimen
	<b>Interpretation of Test Data:</b> The distance travelled by the flame front is converted to critical radiant heat flux required for ignition using a standard radiant heat flux curve.		
28	<b>Nord Test Method NT Fire 007</b> Flooring. Fire spread and smoke generation	To determine the tendency of a flooring to spread fire and generate smoke.	A burning wooden crib is placed on the surface of a specimen mounted at 30° to the horizontal and an air flow forced over the exposed

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
			surface. Times of specimen ignition, extinguish of flames and die out of glow are recorded. Damage inflicted on the specimen and its size, and absorption of light by the smoke are observed. Four specimens are tested (two in each direction).
	<b>Interpretation of Test Data:</b> The resulting times, damage distance and smoke generation are used to compare the fire contribution of competing flooring materials.		
29	<b>BS EN 60332 Part 2-1</b> Tests on Electric and optical fibre cables under Fire Conditions. Test for vertical flame propagation for single insulated wire or cable. (Formerly BS EN 50265-2-1, formerly BS 4066-1)	The test is intended for type approval testing, and may be referred to in cable standards.	The sample shall be clamped at each end to position it vertically in the middle of a three sided metallic screen.
	<b>Interpretation of Test Data:</b> After burning has ceased, the surface shall be wiped clean and the charred or affected portion shall not have reached within 50 mm of the lower edge of the top clamp.		
30	<b>BS EN 50266 Parts 1 and 2-1 to 2-5</b> Common test methods for cables under fire conditions. Test for vertical flame spread on vertically mounted bunched wires or cables. (Formerly BS 4066 Part 3 = IEC 60332 Part 3)	A method of type approval to define the ability of bunched cables to restrain flame propagation in defined conditions regardless of their application, i.e. power, telecommunications etc. If required the Oxygen Index (OI) is also to be measured	Samples are mounted on the appropriate ladder and the burner shall be arranged horizontally at a distance of 75 mm $\pm$ 5 mm and the burner flame centred between two cross bars on the ladder for a period of 20 min. If burning has not ceased after a maximum of 1 hr from completion of the flame test the flame should be extinguished.
	<b>Interpretation of Test Data:</b> After burning has ceased, the surface shall be wiped clean. All soot is ignored if the original surface is not damaged. The maximum extent of damage is measured to one decimal place from the bottom edge of the burner to the onset of char. The maximum extent of char should not have reached a height exceeding 2.5 m above the bottom edge of the burner, neither at the front nor the rear of the ladder.		
31	<b>BS 6387</b> Specification for performance requirements for cables required to maintain circuit integrity under fire conditions	Lists the applicable tests depending upon the category of cable. Apart from tests relating to Electrical requirements, Bending characteristics, Impact and the requirements of BS 4066 Part 1 there are tests for: Resistance to fire alone Resistance to fire with water Resistance to fire with mechanical shock	The fire tests requires that no fuse shall be ruptured nor any lamp extinguished during the test

Test No.	REFERENCES	PURPOSE OF TEST	DESCRIPTION
	<b>Interpretation of Test Data:</b> Cables are categorised by a letter symbol or series of symbols according to the requirements for fire characteristics which they meet		
32	<b>Def Stan 80-77</b> <b>Def Stan 80-78</b> Fire resistance	To assess the fire resistance of paint on a steel substrate	Specimens are supported vertically in a test cabinet. Flame from a gas burner is allowed to impinge on the unpainted side for 60 seconds. The behaviour of the paint film is observed and tests are made for evolution of flammable gases.
	<b>Interpretation of Test Data:</b> Characteristics determined are blistering, glowing of charred film, detachment from the substrate and evolution of flammable gases.		

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This is the final report of Applied Research Program (ARP) project 11gy “Technologies for Fire and Damage Control and Condition Based Maintenance”. The project objective was to develop an improved understanding of how materials, sensors and sensor systems choices impact the sustainability and supportability of new build ships from both the damage control and condition based maintenance perspectives.

Specifications, standards and methods for the evaluation of the fire performance of non-metallic materials are reviewed. Although no one method can be used to rank materials, Cone calorimetry is the test method that provides the most useful information on how materials might perform in a fire. A volume sensor system (VSS), named the Canadian Demonstrator Prototype (CDP), was purchased and evaluated on the United States Naval Research Laboratory fire research ship the ex-USS Shadwell. A volume sensor system monitors a space for fire and damage events using video and infrared cameras, infrared and ultraviolet spectral sensors and an acoustic sensor. The system also has data fusion software that analyses the sensor input and determines if the input is consistent with a fire or damage event or is the result of shipboard activities that are not related to fire and damage events. The results of the testing indicated that the system could differentiate between real fire and damage scenarios and shipboard activities and events that are not related to fire and damage events and could therefore reduce false alarms. A condition based monitoring (CBM) diesel engine lubricating oil sensor suite and system was developed and trialled on an operational Canadian Patrol Frigate. The goal of this program is to base maintenance on the condition of the engine and its oil as opposed to performing time based maintenance. This will enable ship’s crews to focus maintenance efforts on engines where it is required and eliminate maintenance when it is not required. The effectiveness of water mist fire suppression systems was modeled using one and two zone models and a computational fluid dynamics (CFD) model. The results of the modeling studies were compared to those from large scale fire tests to validate their accuracy. Improvements in the fire and flammability performance of polymeric materials using nano additives and other strategies were also investigated. It was found that some of the additives improved the fire and flammability performance of the polymeric materials substantially.

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Damage Control Technologies; Fire Suppression; Volume Sensor; Condition Based Monitoring; Materials; Fire Properties; Water Mist System; CFD Modeling



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